

# ANNEX 7 Uncertainty

The annual U.S. Inventory presents the best effort to produce single-point estimates for greenhouse gas source and sink categories in the United States. These estimates were generated according to the UNFCCC reporting guidelines, following the recommendations set forth in the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997) and the *IPCC Good Practice Guidance* (IPCC 2000). This Annex provides an overview of the uncertainty analysis conducted to support the U.S. Inventory, describes the sources of uncertainty characterized throughout the Inventory associated with various source categories (including emissions and sinks), and describes the methods through which uncertainty information was collected, quantified, and presented.

## 7.1. Overview

Some of the current inventory estimates, such as those for CO<sub>2</sub> Emissions from Fossil Fuel Combustion for example, are considered highly accurate; the uncertainty associated with them is therefore minimal. Other categories of emissions exist, however, for which the inventory emission estimates are considered less certain. The uncertainties that surround these estimates can be attributed to (1) scientific (or model) uncertainty, arising when emission and/or removal processes are not completely understood, and resulting in the use of estimation methodologies based on incomplete or incorrect information; or to (2) a lack of precise input data such as emission factors and activity data (i.e., parameter uncertainty).

Parameter uncertainty is the principal type and source of uncertainty associated with national inventory estimates. Parameter uncertainty has been quantified for most emission sources in the U.S. Inventory. While scientific uncertainty can be evaluated by comparing model results with those of other models developed to characterize the same emission (or removal) process and through sensitivity analysis, it would be very difficult—if not impossible—to quantify the model uncertainty associated with most inventory estimates (primarily because, in most cases, only a single model has been developed to estimate emissions for any one source). Model uncertainty was not quantified in this report, though it may be discussed qualitatively.

The primary purpose of the uncertainty analysis conducted in support of the U.S. Inventory is to quantify parameter uncertainty and to evaluate those parameters within the methodologies used to estimate emissions to determine the uncertainty associated with the emission (and removal) estimates presented in the body of this report. By helping to examine data sources, the U.S. Inventory uncertainty analysis provides a strong foundation on which to base future improvements and revisions to the analyses and the Inventory process. For each source category, the analysis highlights opportunities for changes to data measurement, data collection, and calculation methodologies.

## 7.2. Methodology and Results

The United States has developed a QA/QC and uncertainty management plan in accordance with the IPCC Good Practice Guidance. Like the quality assurance/quality control plan, the uncertainty management plan is part of a continually evolving process. An important component of the U.S. Greenhouse Gas Inventory Program, the uncertainty management plan provides for a quantitative assessment of the inventory analysis itself, thereby contributing to continuing efforts to understand both what causes uncertainty and how to improve inventory quality (EPA 2002). Although the plan provides both general and specific guidelines for implementing quantitative uncertainty analysis, its components are intended to evolve over time, consistent with the inventory estimation process. The U.S. plan includes procedures and guidelines, and forms and templates, for developing quantitative assessments of uncertainty in the national Inventory estimates.

The IPCC Good Practice Guidance recommends two approaches—Tier 1 and Tier 2—for developing quantitative estimates of uncertainty in the inventory estimate of individual source categories and the overall inventory. The elements of the two approaches are described with their results in the following sections. The United States is in the process of implementing a multi-year strategy to develop quantitative estimates of uncertainty for all source categories. Over time, the United States plans to implement a Tier 2 uncertainty analysis for all sources. As the current year represents the second year of this three- to five-year process, a Tier 2 approach was implemented wherever possible; six source categories that were previously analyzed using a Tier 1 approach were

improved for the current Inventory to include a Tier 2 uncertainty analysis. These include Aluminum Production (IPCC Source Category 2F7), Electrical Transmission and Distribution (IPCC Source Category 2F7), Semiconductor Manufacture (IPCC Source Category 2F6), Magnesium Production and Processing (IPCC Source Category 2C4), Wastewater Treatment (IPCC Source Category 6B), and Human Sewage (Domestic Wastewater) (IPCC Source Category 6B2).

For those sources where a Tier 2 approach was not feasible this year, a Tier 1 approach was implemented. A Tier 1 approach was only adopted for ten source categories, as shown in Figure 7-1. Quantitative uncertainty estimates were not calculated for CO<sub>2</sub> from Natural Gas Flaring (IPCC Source Category 1B2), although emissions from the source do appear in the body of this report. While future efforts will be made to quantify these uncertainties, efforts to date have focused on those source categories characterized by uncertainties expected to have the greatest impact on an overall uncertainty assessment of the inventory. Emissions and sinks from International Bunker Fuels, Biomass Burning, and Ambient Air Pollutants are not included in total emissions estimated for the U.S. Inventory; therefore, no quantitative uncertainty estimates have been developed for these sources.

### Characterization of Uncertainty

Both Tier 1 and Tier 2 uncertainty analyses require input variables that are well-characterized. Ideally, each input (i.e., emission factor, activity data point, etc.) would be determined through the careful study of accurately measured data. The variability in such data would provide a reliable estimate of the random uncertainty associated with the measured data. Unfortunately, it is rarely the case that inventory estimates are based on such carefully measured data; more often, inputs are based on a limited number of observations, on expert judgment, or on IPCC recommendations. The characterization of uncertainty associated with these inputs, then, relies heavily on expert judgment.

Because Tier 2 Monte Carlo simulation is both more flexible and more powerful than the Tier 1 method, it is the preferred method for all source categories where sufficient and reliable data is available to characterize inputs. Unless particularly convincing measurements or expert judgment determine otherwise, the probability density functions (PDF) incorporated in the Monte Carlo analyses are limited to uniform, triangular, or normal distributions. The choice among these three PDFs depends largely on observed or measured data and expert judgment. The most common input PDF modeled among all source category analyses that used Monte Carlo simulation was the normal distribution, requiring that the mean and standard deviation of an input's distribution be known or determined. The result of such an analysis typically approximates a normally distributed curve; an example of such a curve is shown in Figure 7-1. If it can be assumed that a particular dataset (e.g., emission factor) is normally distributed, this input distribution generally yields a "tighter" confidence interval and more robust output from the method developed to estimate emissions than does a similar dataset characterized by a uniform distribution (i.e., by a minimum and maximum value).

#### **Figure 7-1. Example of a Normally-Distributed Curve, CH<sub>4</sub> Emissions from Wastewater Treatment**

The following sections present results based on Tier 1 or Tier 2 assessments of source category-level uncertainty.

### Tier 1 Uncertainty Analyses

The Tier 1 method for estimating uncertainty is based on the error propagation equation, and its derivations as presented in the IPCC Good Practice Guidance, by combining uncertainties associated with activity data and those associated with emission (or other) factors. Inherent in employing the Tier 1 method is the assumption, for each source category, that both activity data and emission factor values are approximately normally distributed, that the coefficient of variation is less than 30 percent, and that the values to be combined are not correlated. Under the direction of the uncertainty analysis coordinator, U.S. Inventory analysts determine the uncertainty associated with source category emissions using standard spreadsheet software. The results are presented for each source category in the body of this report, and are summarized below.

**Table 7-1: Uncertainty Estimates Developed Using Tier 1 Uncertainty Analysis**

Source Category (IPCC Source Category)	Gas	Base Year Emissions*	2003 Emissions	Uncertainty	Trend Uncertainty	Key Source
		(Tg CO <sub>2</sub> Eq.)		(Percent of 2003 Emissions)		
<b>INDUSTRIAL PROCESSES</b>						
Nitric Acid Production (IPCC Source Category 2B2)	N <sub>2</sub> O	17.8	15.8	17%	13%	
Adipic Acid Production (IPCC Source Category 2B3)	N <sub>2</sub> O	15.2	6.0	9%	5%	✓
HCFC-22 Production (IPCC Source Category 2E1)	HFC-23	27.0	12.3	10%	5%	✓
<b>SOLVENT AND OTHER PRODUCT USE</b>						
Nitrous Oxide Product Usage (IPCC Source Category 3D)	N <sub>2</sub> O	4.3	4.8	7%	11%	
<b>AGRICULTURE</b>						
Agricultural Soil Management (IPCC Source Category 4D)	N <sub>2</sub> O	253.0	253.5	82%	26%	✓
Field Burning of Agricultural Residues (IPCC Source Category 4F)	N <sub>2</sub> O	0.4	0.4	68%	+	
Field Burning of Agricultural Residues (IPCC Source Category 4F)	CH <sub>4</sub>	0.7	0.8	69%	1%	
<b>LAND-USE CHANGE AND FORESTRY (SINK)</b>						
Changes in Agricultural Soil Carbon Stocks (IPCC Source Category 5.B.1)**	CO <sub>2</sub>	9.5	9.5	76%	21%	
N <sub>2</sub> O Fluxes from Settlements Remaining Settlements (IPCC Source Category 5.E.1)	N <sub>2</sub> O	5.5	6.0	-94 to +483%	38%	
N <sub>2</sub> O Fluxes from Forest Land Remaining Forest Land (IPCC Source Category 5.A.1)	N <sub>2</sub> O	0.1	0.4	-96 to +483%	250%	
Changes in Carbon Stocks in Urban Trees (IPCC Source Category 5E1)	N <sub>2</sub> O	(58.7)	(58.7)	37%	52%	

+ Value is less than 0.05 percent.

\*Base Year is 1990 for sources of CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O; the United States has chosen 1995 as the base year for HFCs, PFCs, and SF<sub>6</sub>.

\*\*Changes in Agricultural Soil Carbon Stocks in this table includes only that portion of the source category attributable to liming.

Table 7-1 shows base year (1990 or 1995) and current year (2003) emissions for each source category. The combined uncertainty for each source category is expressed as a percent of the total 2003 emissions estimated for that source category. Source category trend uncertainty is described below.

## Tier 2 Uncertainty Analyses

If the uncertainties associated with input variables are significantly large, if the distributions underlying the input variables are not characterized by a normal distribution, and/or if the uncertainties have significant correlation, adoption of the Tier 2 method is the preferred approach. The Tier 2 method employs the Monte Carlo Stochastic Simulation technique. This method replicates the equation (or set of equations) used to model the emission (or removal) process for a particular source category many times, using a large sample of randomly-selected values to do so. For each iteration, values for emission factors and activity data are generated through random sampling according to their individual input distributions, or probability density functions. These distributions are assigned as inputs to the analysis for each variable, and depend on observed variances that can be based on measurement studies or on expert judgment. The distribution and frequency of emission values modeled over each series of iterations provide the results of the analysis, and the upper and lower bounds of a 95 percent confidence interval are reported in the body of the report for each source category, and are summarized below in Table 7-2.

**Table 7-2: Uncertainty Estimates Developed Using Tier 2 Uncertainty Analysis**

IPCC Source Category	Gas	Base Year Emissions*	2003 Emissions	2003 Uncertainty (95% Confidence Interval)		Change from Base Year to 2003	Range of Likely Change From Base Year to 2003		U.S. Inventory Key Sources
		Tg CO <sub>2</sub> Eq.	Tg CO <sub>2</sub> Eq.	Low	High	Percent	Low	High	
ENERGY									
Carbon Dioxide Emissions from Fossil Fuel Combustion (portion of IPCC Source Category 1A)	CO <sub>2</sub>	4,711.7	5,551.6	-1%	6%	18%	16%	24%	✓
Carbon Stored in Products from Non-Energy Uses of Fossil Fuels (portion of IPCC Source Category 1A)	CO <sub>2</sub>	108.0	118.0	-17%	11%	9%	-10%	21%	
Stationary Combustion (excluding CO <sub>2</sub> ) (portion of IPCC Source Category 1A)	CH <sub>4</sub>	7.8	6.7	-28%	99%	-15%	-38%	70%	
Stationary Combustion (excluding CO <sub>2</sub> ) (portion of IPCC Source Category 1A)	N <sub>2</sub> O	12.3	13.8	-22%	184%	13%	-12%	221%	
Mobile Combustion (excluding CO <sub>2</sub> )	CH <sub>4</sub>	4.8	2.7	-9%	4%	-44%	-49%	-42%	
Mobile Combustion (excluding CO <sub>2</sub> )	N <sub>2</sub> O	43.7	42.1	-16%	26%	-4%	-19%	21%	✓
Coal Mining (IPCC Source Category 1B1a)	CH <sub>4</sub>	81.9	53.8	-4%	4%	-34%	-37%	-32%	✓
Abandoned Underground Coal Mines (IPCC Source Category 1B1a)	CH <sub>4</sub>	6.1	6.4	-16%	22%	6%	-11%	29%	
Petroleum Systems (IPCC Source Category 1B2a)	CH <sub>4</sub>	20.0	17.1	-30%	200%	-14%	-40%	157%	✓
Natural Gas Systems (IPCC Source Category 1B2b)	CH <sub>4</sub>	128.3	125.9	-31%	32%	-2%	-32%	30%	✓
Municipal Solid Waste Combustion (IPCC Source Category 1A5)	CO <sub>2</sub>	10.9	18.8	-19%	15%	72%	39%	98%	
Municipal Solid Waste Combustion (IPCC Source Category 1A5)	N <sub>2</sub> O	0.4	0.5	-71%	192%	10%	-68%	221%	
INDUSTRIAL PROCESSES									
Iron and Steel Production (IPCC Source Category 2C1)	CO <sub>2</sub>	85.4	53.8	-41%	42%	-37%	-63%	-11%	✓
Iron and Steel Production (IPCC Source Category 2C1)	CH <sub>4</sub>	1.3	1.0	-11%	11%	-22%	-31%	-14%	
Cement Manufacture (IPCC Source Category 2A1)	CO <sub>2</sub>	33.3	43.0	-8%	8%	29%	19%	39%	✓
Ammonia Production (IPCC Source Category 2B1)	CO <sub>2</sub>	12.6	9.1	-15%	15%	-28%	-38%	-17%	✓
Urea Application (IPCC Source Category 2B1)	CO <sub>2</sub>	6.8	6.5	-8%	8%	-4%	-12%	3%	✓
Lime Manufacture (IPCC Source Category 2A2)	CO <sub>2</sub>	11.2	13.0	-8%	8%	16%	7%	25%	
Limestone and Dolomite Use (IPCC Source Category 2A3)	CO <sub>2</sub>	5.5	4.7	-7%	8%	-15%	-21%	-8%	
Soda Ash Manufacture and Consumption (IPCC Source Category 2A4)	CO <sub>2</sub>	4.1	4.1	-4%	4%	-1%	-5%	2%	
Titanium Dioxide Production (IPCC Source Category 2B5)	CO <sub>2</sub>	1.3	2.0	-16%	16%	54%	29%	79%	
Phosphoric Acid Production (IPCC Source Category 2A7)	CO <sub>2</sub>	1.5	1.4	-18%	18%	-10%	-26%	7%	
Ferroalloy Production (IPCC Source Category 2C2)	CO <sub>2</sub>	2.0	1.4	-3%	3%	-31%	-33%	-28%	

IPCC Source Category	Gas	Base Year Emissions*	2003 Emissions	2003 Uncertainty (95% Confidence Interval)		Change from Base Year to 2003	Range of Likely Change From Base Year to 2003		U.S. Inventory Key Sources
		Tg CO <sub>2</sub> Eq.	Tg CO <sub>2</sub> Eq.	Low	High	Percent	Low	High	
Carbon Dioxide Consumption (IPCC Source Category 2B5)	CO <sub>2</sub>	0.9	1.3	-5%	5%	47%	40%	54%	
Petrochemical Production (IPCC Source Category 2B5)	CH <sub>4</sub>	1.2	1.5	-7%	7%	30%	21%	39%	
Petrochemical Production (IPCC Source Category 2B5)	CO <sub>2</sub>	2.2	2.8	-10%	10%	25%	13%	38%	
Silicon Carbide Production (IPCC Source Category 2B4)	CH <sub>4</sub>	+	+	-10%	10%	-67%	-70%	-63%	
Substitution of Ozone Depleting Substances (IPCC Source Category 2F)	HFC & PFC	24.4	99.5	-10%	9%	307%	267%	342%	✓
Electrical Transmission and Distribution (IPCC Source Category 2F7)	SF <sub>6</sub>	21.7	14.1	-13%	14%	-35%	-43%	-26%	✓
Aluminum Production (IPCC Source Category 2C3)	CO <sub>2</sub>	6.3	4.2	-34%	40%	-33%	-56%	-6%	
Aluminum Production (IPCC Source Category 2C3)	CF <sub>4</sub>	10.5	3.3	-11%	11%	-69%	-72%	-65%	
Aluminum Production (IPCC Source Category 2C3)	C <sub>2</sub> F <sub>6</sub>	4.8	0.5	-12%	13%	-89%	-90%	-88%	✓
Semiconductor Manufacture (IPCC Source Category 2F6)	HFC, PFC, SF <sub>6</sub>	5.0	4.6	-20%	23%	-8%	-27%	13%	
Magnesium Production and Processing (IPCC Source Category 2C4)	SF <sub>6</sub>	5.6	3.0	-11%	13%	-47%	-53%	-40%	
<b>AGRICULTURE</b>									
Enteric Fermentation (IPCC Source Category 4A)	CH <sub>4</sub>	117.9	115.0	-11%	18%	-2%	-13%	15%	✓
Manure Management (IPCC Source Category 4B)	CH <sub>4</sub>	31.2	39.1	-18%	20%	26%	3%	51%	✓
Manure Management (IPCC Source Category 4B)	N <sub>2</sub> O	16.3	17.5	-16%	24%	8%	-9%	34%	
Rice Cultivation (IPCC Source Category 4C)	CH <sub>4</sub>	7.1	6.9	-58%	101%	-3%	-59%	95%	
<b>LAND-USE CHANGE AND FORESTRY (SINK)</b>									
Changes in Forest Carbon Stocks (IPCC Source Category 5A1)	CO <sub>2</sub>	(949.3)	(752.7)	-49%	49%	21%	-18%	60%	
Changes in Agricultural Soil Carbon Stocks (IPCC Source Category 5B1)**	CO <sub>2</sub>	(17.5)	(16.1)	-148%	136%	8%	-117%	133%	
Changes in Yard Trimming and Food Scrap Carbon Stocks in Landfills (IPCC Source Category 5E1)	CO <sub>2</sub>	(26.0)	(10.1)	-74%	31%	61%	49%	73%	
<b>WASTE</b>									
Wastewater Treatment (IPCC Source Category 6B)	CH <sub>4</sub>	24.8	36.8	-32%	37%	48%	1%	102%	✓
Human Sewage (Domestic Wastewater) (IPCC Source Category 6B2)	N <sub>2</sub> O	13.0	15.9	-74%	88%	22%	-68%	129%	
Landfills (IPCC Source Category 6A1)	CH <sub>4</sub>	172.2	131.2	-36%	16%	-24%	-51%	-12%	✓

\*Base Year is 1990 for sources of CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O; the United States has chosen 1995 as the base year for HFCs, PFCs, and SF<sub>6</sub>.

\*\*Changes in Agricultural Soil Carbon Stocks in this table includes only that portion of the source category attributable to mineral and organic soils.

+ Emissions from this source are less than 0.05 Tg CO<sub>2</sub> Eq.

## Trend Uncertainty

In addition to estimates of uncertainty associated with the current year's emission estimates, this Annex also presents estimates of trend uncertainty. The trend is the difference between emissions estimated for the base year and that estimated for the current year. For Tier 1 analyses, trend uncertainty is estimated using the sensitivity of the calculated difference between base year and 2003 emissions to an incremental (i.e., 1 percent) increase in one or both of these values. Two sensitivities are expressed as percentages: Type A sensitivity highlights the effect on the difference between base and current year emissions caused by a 1 percent change in both, while Type B sensitivity highlights the effect caused by a change to only the current year's emissions. Both sensitivities are simplifications introduced in order to analyze correlation between base and current year estimates. Once calculated, the two sensitivities are combined using the error propagation equation to estimate overall trend uncertainty. For Tier 2 analyses, trend uncertainty is estimated using Monte Carlo Stochastic Simulation; the range of likely change from base year to 2003 is shown in Table 7-2. For the purposes of estimating trend uncertainty in the U.S. Inventory, 1990 is the base year for all CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O source categories, while 1995 is the base year for all sources of HFCs, PFCs, and SF<sub>6</sub>.

## 7.3. Uncertainty Estimation as a Process

The IPCC Good Practice Guidance suggests that the resources expended for characterizing uncertainty associated with an inventory input should be proportional to its importance to the overall uncertainty assessment of the inventory. Therefore, to identify those input variables to which the overall uncertainty in the inventory is highly sensitive, an iterative approach is undertaken wherein, in the first iteration of an uncertainty analysis, initial assessments of the uncertainty of input variables are made and propagated through the inventory in order to preliminarily identify the main sources of uncertainty (in terms of key input variables); subsequently, uncertainty in the key input variables are characterized more accurately through detailed investigations.

Identifying the sources of uncertainties in the emission and sink estimates of the Inventory and quantifying the magnitude of the associated uncertainty is the crucial first step towards improving those estimates. Quantitative assessment of the parameter uncertainties may also provide information about the relative importance of input parameters (such as activity data and emission factors), based on their relative contribution to the uncertainties within the source category estimates. Such information can be used to prioritize resources with a goal of reducing uncertainties over time within or among inventory source categories and their input parameters. In the current Inventory, potential sources of model uncertainty have been identified for some emission sources, and preliminary parameter uncertainty estimates have been developed for the vast majority of emission source categories.

Thus, a multi-year, multi-stage approach to the quantitative assessment of uncertainty of the U.S. Inventory is underway; the current year's assessment identifying the key sources of uncertainty in the Inventory is the result of the second annual quantitative assessment of uncertainty in the U.S. Inventory. Under this approach, quantitative estimates of uncertainty associated with the overall inventory are being conducted in stages, over a period of three to five years, such that a credible uncertainty assessment for individual source categories and the overall inventory can be developed relying on the IPCC Tier 2 approach.

## 7.4. Planned Improvements

To estimate emissions and removals from the inventory source categories, IPCC methodologies were applied and supplemented by country-specific methodologies and data. In future inventory reports, additional efforts will be necessary to improve estimation methodologies and data collection procedures, thereby reducing uncertainty. Specific areas that require further research include:

- Incorporating excluded emission sources. Quantitative estimates of the uncertainties associated with some of the sources and sinks of greenhouse gas emissions are not available at this time. In the future, efforts will focus on associating uncertainty figures with all those source categories for which emissions or removals are estimated.
- Improving the accuracy of emission factors. Further research is needed in some cases to improve the accuracy of emission factors used to calculate emissions from a variety of sources. For example, the

accuracy of current emission factors applied to CH<sub>4</sub> and N<sub>2</sub>O emissions from stationary and mobile combustion is highly uncertain.

- Collecting detailed activity data. Although methodologies exist for estimating emissions for some sources, problems arise in obtaining activity data at a level of detail in which aggregate emission factors can be applied. For example, the ability to estimate emissions of SF<sub>6</sub> from electrical transmission and distribution is limited due to a lack of activity data regarding national SF<sub>6</sub> consumption or average equipment leak rates.

The approach to uncertainty analysis employed in this Inventory recognizes that developing quantitative assessments of uncertainty is not an end in itself, but a crucial step toward improving inventory estimates through systematic analysis and identification of various sources of uncertainty in the inventory estimates. Further, since the reliability of quantitative assessment of uncertainty in the overall Inventory depends upon the accuracy of the uncertainty in the input data, the U.S. plan underscores the importance of developing credible quantitative uncertainty data for the activity- and emission factor-related inventory variables that underlie the emission estimates. This will require extensive use of expert elicitation to obtain the experts' quantitative judgments of uncertainty in the inventory input variables, as many of the inventory estimates for the input variables are point estimates and, often, statistical estimates of uncertainty in these estimates are not available. The United States plans to continue to combine detailed expert elicitation with less formal interviews (based on resource availability) to increase the availability of uncertainty data for the inventory input variables, and ultimately, allow an overall level of uncertainty for the Inventory to be estimated.

## References

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